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A tale of two planets: Disparate evolutionary models for Mars inferred from radiogenic isotope compositions of Martian meteorites

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The radiogenic isotopic compositions of basaltic Martian meteorites (shergottites) and clinopyroxene/olivine cumulate meteorites (nakhlite/chassignites) are used to define the global evolution of Mars. However, the two main groups of meteorites demonstrate that their sources underwent divergent styles of magmatic evolution. The shergottites portray a planet that differentiated ~4.52 billion years ago via solidification of a magma ocean, producing incompatible element-depleted and -enriched reservoirs that remained isolated until melt production. In contrast, the reservoir from which the nakhlite/chassignites derive may have formed earlier, produced melts that fractionated Sm/Nd and Hf/W differently, was compositionally less variable, and experienced a significantly more complex history following primordial differentiation than the shergottite sources. The disparate histories recorded by these two groups of meteorites elucidate important questions that could be addressed by acquiring additional samples. Obtaining samples that shared the isotopic systematics of the shergottites would provide confidence that extrapolating the primordial differentiation history of Mars from shergottite radiogenic isotope systematics is reasonable. Returned samples from Mars will also constrain the physical locations of the meteorite source regions, providing insights into the general structure of the Martian mantle. In addition, they will help constrain the phases present in the martian mantle during melting and the conditions under which they are stable. Finally, identifying an evolved lithology that satisfies the geochemical and isotopic constraints placed on the incompatible element-enriched endmember observed in the shergottites would define the nature of magmatic evolution on Mars and whether it is more akin to processes on the Earth or the Moon.

Mars | isotopes | sample return | chronology | planetary differentiation

Broad-scale questions regarding the origin and evolution of Mars, such as how and when it differentiated and when and whether it experienced global-scale geological processes such as mantle convection and plate tectonics, can be addressed through radiogenic isotope analysis of Martian samples. This reflects the fact that radiogenic isotope systems tightly constrain the composition, geologic history, and ages of reservoirs from which igneous samples are derived. From the analysis of short-lived, now-extinct, isotope systems, it is evident that Mars underwent global-scale planetary differentiation, forming a core, mantle, and crust, early in its history (e.g., refs. 1–4). Similarly, long-lived extant isotope systems define young crystallization ages for most SNC meteorites, demonstrating that magmatic activity occurred very recently on Mars (e.g., refs. 5–8). However, despite these relatively unambiguous conclusions, the various groups of Martian meteorites do not share a common evolutionary history (e.g., refs. 9–12), obfuscating understanding of the details of global-scale processes such as primordial differentiation, melt production, and the physical location of geochemical reservoirs. In particular, the isotopic systematics of the shergottites imply that Mars differentiated early into primordial reservoirs that remained isolated until the time of parental melt production (e.g., refs. 1, 3, and 13). In contrast, the isotopic systematics of the nakhlite/chassignites suggest that after formation by primordial differentiation, their sources were modified by open system processes, such as metasomatism, that altered their elemental and isotopic compositions (e.g., refs. 2 and 14–16). Here, we explore the radiogenic isotopic systematics of the shergottites and nakhlites/chassignites in order to elucidate differences in the geologic histories of their source regions. This purpose of this effort is to identify questions regarding the global evolution of Mars that might be addressed through the return of samples.

Rubidium–strontium, Sm–Nd, and Lu–Hf isotopic systematics of the shergottites and nakhlites/chassignites are used to calculate the Rb/Sr, Sm/Nd, and Lu/Hf ratios of their sources. These ratios, in turn, provide insights into the processes associated with the origin and evolution of Mars. The mathematics and underlying assumptions associated with some of these calculations were developed by Nyquist et al. (17) and are reviewed in refs. 3 and 18. Our focus is solely on the shergottites and nakhlites/chassignites because they are by far the most abundant meteorite groups, representing about 95% of known Martian meteorites (19), and have the most broadly constrained radiogenic isotopic systematics. These samples, however, are not representative of the entire planet, as implied by compositionally distinct and older Martian meteorites such as NWA 7034 and ALH 84001 (19). Thus, the questions based on the SNC meteorites represent

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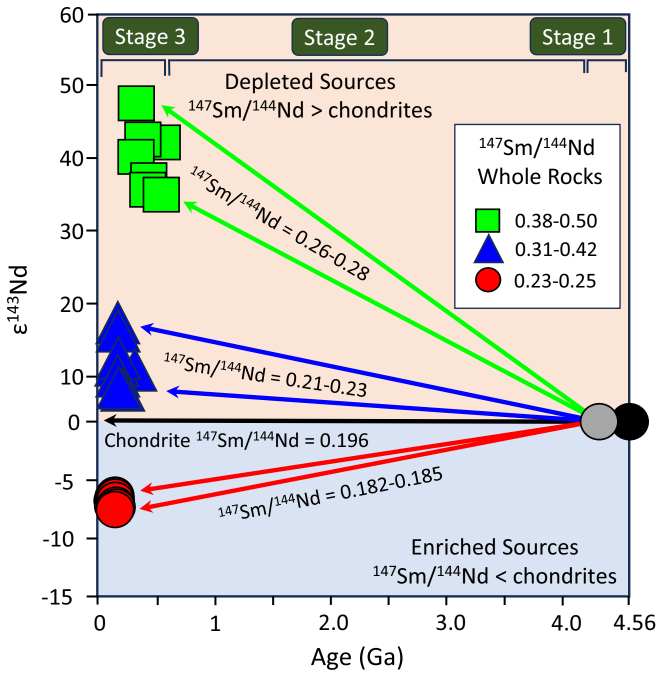

Fig. 1. Samarium-neodymium isotopic evolution of the shergottites. $\varepsilon^{143}Nd$ is the deviation of $^{143}Nd/^{144}Nd$ from chondritic evolution in parts per 10^4. The first evolution stage occurs in an undifferentiated reservoir with Sm-Nd isotopic systematics of chondritic meteorites until primordial silicate differentiation at 4.52 Ga. Chondritic meteorites have Sm and Nd compositions similar to the Sun and therefore represent the Sm/Nd composition of bulk Mars. The second stage of growth occurs in the sources of the shergottites that were formed during primordial differentiation of Mars at 4.52 Ga. The slopes of the growth curves (arrows) are in proportion to the $^{147}Sm/^{144}Nd$ of their sources. Red circles are shergottites with $^{147}Sm/^{144}Nd$ sources <0.196 (enriched shergottites), green squares are shergottites with $^{147}Sm/^{144}Nd$ sources >0.25 (depleted shergottites), and blue triangles have intermediate $^{147}Sm/^{144}Nd$ sources (intermediate shergottites). The shergottites are extracted from their sources at times defined by their crystallization ages. A third stage of growth occurs in the rocks after they were extracted from their sources. The melts have $^{147}Sm/^{144}Nd$ that differ from their sources and therefore lie on growth curves with different slopes (*Inset*). Modified from ref. 18. Data are from refs. 4, 12, 18, and 25.

only a subset of those pertinent to understanding its planetary evolution. With these questions in mind, we explore how samples returned from Mars might be used to develop a more coherent model of planetary evolution.

Shergottites and Nakhlite/chassignite Meteorites

The shergottite, nakhlites, and chassignite (SNC) meteorites represent the vast majority of Martian meteorites and are the basis of this discussion because their radiogenic isotopic systematics are well constrained. A recent summary of the petrologic, geochemical, and chronological characteristics of the SNC meteorite suite is provided by Kruijer et al. (19). The shergottites are basaltic rocks with relatively young ages of less than ~600 Ma (5, 6, 19). They are characterized by well-defined relationships between their variable incompatible trace element abundances, ages, radiogenic isotopic compositions, and magmatic oxygen fugacities (e.g., refs. 20 and 21). As a consequence, they constitute the basis for canonical models for the origin and early evolution of Mars (e.g., refs. 1, 2, 13, 21, and 22). The nakhlites and chassignites exhibit chemical, isotopic, and chronological characteristics that are markedly different from the shergottites. The nakhlites are clinopyroxenites with ages of ~1.3 Ga, which, although young in comparison to most meteorites, are considerably older than the shergottites (see, e.g., refs. 5 and 6). The chassignites are ~1.3 Ga old dunites that share incompatible element and isotopic systematics with the nakhlites. Given these similarities, these two types of meteorites are grouped in the following discussion (23). Unlike the shergottites, the nakhlite/chassignites exhibit little variation in their incompatible element, isotopic, and chronologic systematics, indicating that they are essentially derived from a single source. Models for the origin and evolution of Mars largely ignore these samples (e.g., refs. 3, 4, 12, 21, 24, and 25) because they demonstrate relatively little compositional or isotopic variation and have isotopic characteristics that are inconsistent with most models derived from the much more abundant shergottites.

Both groups of meteorites demonstrate excesses of daughter products of short-lived isotopic systems, such as ^{142}Nd and ^{182}W (2–4, 18, 26–28), indicating that they formed from sources produced early in the history of the Solar System. In addition, mass-independent isotopic compositions of the shergottites and nakhlites as determined for a wide range of elements (e.g., O, Ti, Cr, Zn, and Zr) are identical within reasonable uncertainty (e.g., refs. 29–34), indicating that Martian mantle sources are composed of accreted material that was either homogeneous to begin with or was homogenized immediately after accretion. Other than this, shergottites and nakhlites/chassignites share few other isotopic similarities. Below we examine the key isotopic differences between the shergottites and the nakhlite/chassignite meteorites to help identify questions relevant to future Mars sample return.

Constraining Primary Differentiation and the Nature of the Martian Mantle

A combination of both short- and long-lived isotopic systems has been used to constrain the primary differentiation history of Mars. However, distinct evolutionary pathways are elucidated by the isotopic systematics of shergottites and nakhlites/chassignites. Isotopic data demonstrate that the shergottite source regions formed early in Solar System history (Fig. 1) in two discrete stages of growth. The first stage occurred in a single undifferentiated reservoir with a composition similar to estimates of the bulk planet and the second growth stage occurred in differentiated mantle and/or crustal reservoirs with fractionated parent/daughter isotope ratios (e.g., refs. 1, 3, 4, 13, 19, 24, 25, and 35). The picture of Martian evolution that has emerged from the radiogenic isotopic systematics of the shergottites is that of a planet that underwent silicate differentiation in a global magma ocean between 4.50 and 4.54 Ga (e.g., Fig. 2 *A* and *B*). Global differentiation was followed by a long period of quiescence in which primordial magma ocean reservoirs did not interact significantly until magmatic activity produced the shergottite parental melts between ~150 and ~600 Ma. This implies that, unlike on Earth, geological processes such as crustal recycling, vigorous mantle convection, and by inference plate tectonics, ceased around 4.5 Ga or never developed on Mars. Accordingly, the compositional and isotopic diversity of the shergottites was established by mixing of primordial magma ocean crystallization products near the time of melt production implying that the style of Martian differentiation was similar to that inferred for the Earth's Moon (17, 36–38).

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Consequently, modified versions of the evolutionary models developed for the Moon have proven to be a reasonable basis for understanding the origin and evolution of the shergottites (e.g., refs. 3, 6, 13, 14, 24, 25, 39, and 40).

The model for the formation and evolution of Mars based on the isotopic systematics of the nakhlite/chassignites differs substantially from that inferred from the shergottites. Radiogenic excesses in ^{142}Nd and ^{182}W measured in the nakhlites suggest that Sm/Nd and Hf/W were fractionated early in the history of the planet, probably by primordial differentiation associated with the formation of their sources. However, the origin of the highly elevated ^{182}W of the nakhlites is enigmatic and could either reflect that primordial differentiation occurred even earlier than for the shergottites or involved an unprecedented extent of Hf/W fractionation (e.g., refs. 2, 19, 27, and 35). For this reason, constraining the timescales of primordial differentiation using the nakhlites is difficult. Furthermore, the nakhlite/chassignite source does not appear to have evolved in a simple two-stage process like the shergottites (13, 14, 24). This is indicated in Fig. 2*B* by the observation that nakhlites fall in multistage evolutionary space on a ^{143}Nd-^{142}Nd isochron diagram. Importantly, the multistage evolutionary history of the nakhlite/chassignite sources indicates that they were not fully isolated after their formation and instead must have been modified by processes occurring after primordial differentiation, such as mantle mixing (convection), crustal recycling, metasomatism, and/or protracted melt extraction (14, 24). The geochemical and isotopic investigations of the nakhlite/chassignite sources appear to be most consistent with the addition of a metasomatic component enriched in light-rare-earth-elements to an incompatible element-depleted mantle reservoir (2, 14, 16). Late metasomatism is appealing because it is consistent with evidence for recent volcanic activity on the surface of Mars (e.g., refs. 41–44) that requires the transport of magmas and potentially metasomatic fluids into the upper mantle (16). Despite the probable late addition of metasomatic components, the open system processes recorded in the nakhlite/chassignite source cannot have been so efficient that they erased the enrichments of ^{142}Nd and ^{182}W (2). This is probably not unreasonable, however, because mixing processes resulting in complete erasure of short-lived isotopic anomalies would require ideal proportions of each component to produce, for example, chondrite-like ^{142}Nd isotopic compositions. Thus, the source of the nakhlite/chassignites cannot have shared the same evolutionary history as the shergottite sources. In fact, the observation that the shergottite sources have been isolated since they formed and that the nakhlite/chassignite sources have probably been metasomatized portends very different evolutionary pathways. The complex multistage evolution inferred from the nakhlite/chassignites seems more akin to that of a geologically active body like Earth rather than a geologically inactive body like the Moon that preserves abundant evidence for primordial differentiation.

From the above analysis, it is apparent that different, seemingly mutually exclusive, pictures for the origin and evolution of Mars are derived from the isotopic systematics of the shergottites and the nakhlite/chassignites. The divergent characteristics inferred for the shergottite and nakhlite/chassignite sources are consistent with a Martian mantle that evolves in distinct reservoirs with variable compositions and mineral modes at different pressures and temperatures (e.g., refs. 19, 21, 25, 39, and 40). One possible explanation for the divergent evolution of the shergottite and nakhlite/chassignite sources is that they originated from reservoirs at different depths in a stratified mantle produced during primordial differentiation. Geochemical models of Martian magma ocean solidification predict a stratification of the mantle reflecting the changing sequence of phases crystallized during primordial differentiation (e.g., refs. 39, 40, and 45). Similarly, geophysical models based on data from the InSight lander also suggest that Mars may have such a stratified mantle. Specifically, the lithosphere is composed of a thin crust of 24 to 74 km (46) and an upper mantle that extends to a depth of about 450 to 500 km (46, 47). Below the lithospheric mantle is a low-velocity zone somewhat akin to that observed on Earth, which could be interpreted to indicate that Mars has a convecting lower mantle. Although speculative, convection in the Martian mantle has been previously postulated based on the young ages of the shergottites and numerical simulations (e.g., refs. 48–50). The closed and isolated nature implied for the shergottite sources based on their radiogenic isotope compositions is consistent with derivation from lithospheric mantle domains that have remained isolated and never experienced the homogenization processes that would be associated with convection. The compositional diversity of the shergottites further demands that the Martian lithosphere be compositionally variable. In this scenario, the more complex multistage evolutionary history inferred for the nakhlite/chassignite source would be more consistent with derivation from a deeper, more geologically active mantle that has experienced the addition and removal of silicate melts. Another possibility proposed by Day et al. (16) is that the lithospheric mantle instead is the source of the nakhlite/chassignites and is consequently more geologically active, having experienced metasomatism after primordial differentiation. In this case, the shergottites would be derived from a deeper, nonconvecting mantle source that has remained isolated for most of Martian history.

Alternatively, the mantle heterogeneity recorded by the shergottite and nakhlite/chassignite sources might reflect lateral geologic variations. Circumstantial evidence for such heterogeneity derives from the crustal dichotomy in which the crust in the southern hemisphere of Mars is older, thicker, and at a higher average elevation than the northern hemisphere. Several mechanisms have been proposed for the generation of the dichotomy, including a single mega impact or multiple impacts (e.g., refs. 51–56), degree-1 mantle convection in which upwelling occurs in one hemisphere and downwelling in the other (e.g., refs. 57–59), plate tectonics (e.g., refs. 60 and 61), or mantle overturn (e.g., refs. 39 and 40). In this context, the multistage isotopic evolution of the nakhlites/chassignite sources might be associated with derivation from the southern hemisphere, where late geologic activity in the mantle is hypothesized to have occurred. By contrast, the shergottites might be derived from the northern hemisphere, where the mantle is potentially less active, preserving the ancient isotopic characteristics established during the primordial differentiation of their source regions.

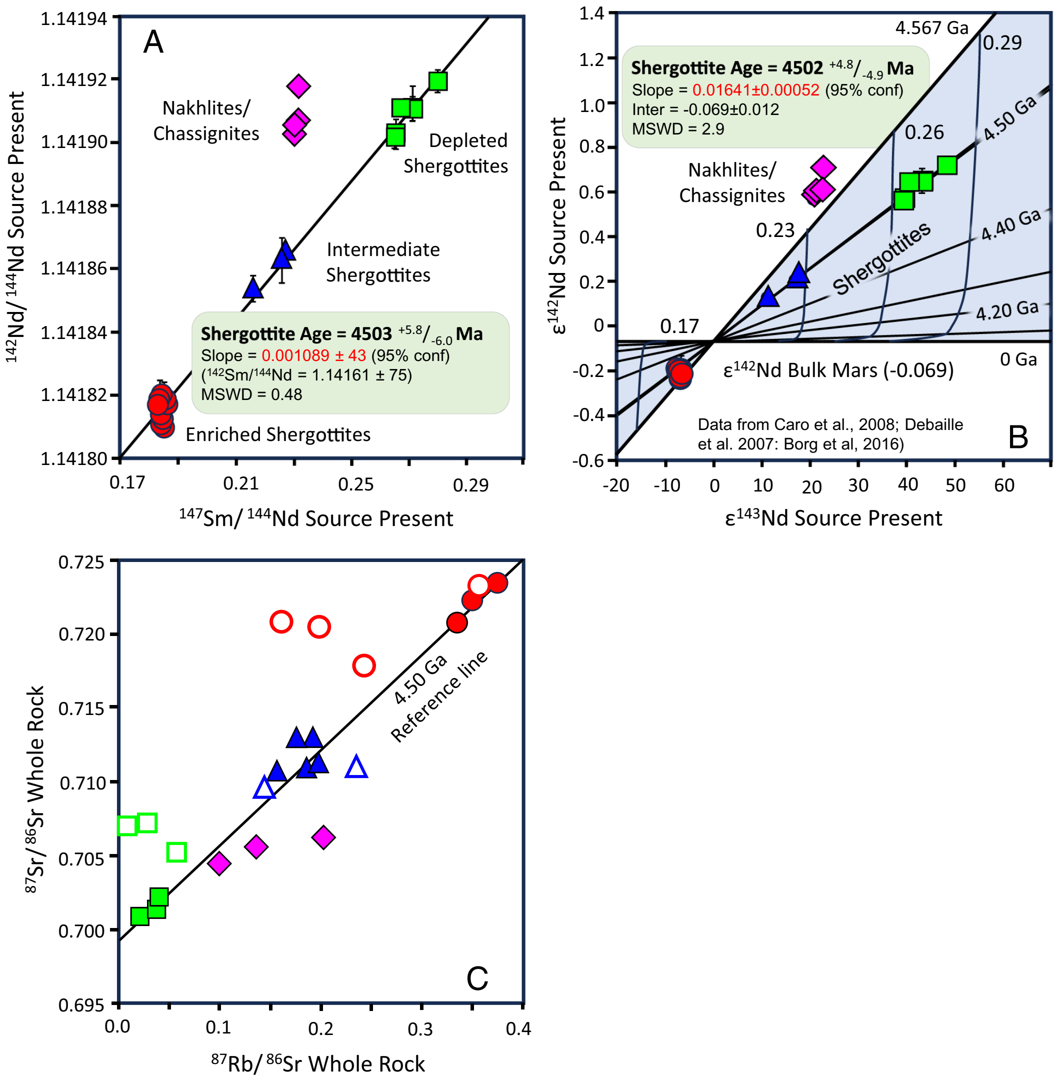

Fig. 2. Model isochrons defining age of planetary differentiation of Mars assuming two stages of planetary growth (see refs. 17, 18, and 25 for model calculations). (*A*) $^{147}Sm/^{144}Nd$ of present meteorite source versus $^{142}Nd/^{144}Nd$ of present meteorite source, (*B*) epsilon ^{142}Nd of present meteorite source versus epsilon ^{143}Nd of present meteorite source, (*C*) $^{87}Rb/^{86}Sr$ of meteorite whole rock versus $^{87}Sr/^{86}Sr$ of meteorite whole rock. The light blue field in *B* represents the region where Sm-Nd evolved in two stages of growth. Data are from refs. 3, 4, 12, 13, 18, and 25. Red circles are shergottites with $^{147}Sm/^{144}Nd$ sources <0.196 (enriched shergottites), green squares are shergottites with $^{147}Sm/^{144}Nd$ sources >0.25 (depleted shergottites), blue triangles have intermediate $^{147}Sm/^{144}Nd$ sources (intermediate shergottites), and pink diamonds are nakhlite/chassignites. Open symbols are desert meteorites demonstrating evidence for terrestrial Sr contamination.

New samples from known and well-characterized locations are required to evaluate the compositional variability of the mantle. Lateral heterogeneity of the Martian mantle would be supported by a relationship between the isotopic systematics recorded by the samples and their location on Mars. In this case, samples from the southern hemisphere would be predicted to exhibit more evidence for a multistage evolution, whereas those from the northern hemisphere would display a simpler two-stage evolutionary history. Likewise, vertical heterogeneity of the mantle would be implied if samples from individual regions/locations on Mars displayed isotopic systematics consistent with both a two-stage and a multistage evolution. The critical information needed to evaluate the compositional variability of the mantle is to determine whether the complexity of the magmatic evolution of individual samples is linked to location on Mars.

Images of rocks from the Jezero crater imply that some are of igneous origin (62), minimally altered (63), and ~3.8 Ga in age (64). Mafic (possibly) intrusive rocks, buried and exhumed lava flows, and a potentially igneous but altered bedrock have been identified by in situ geologic mapping (62, 65, 66). If the isotopic systematics of igneous rocks from Jezero crater mimic those of the shergottites, fundamental inferences about the origin of Mars based on the shergottites would be confirmed. Specifically, if Jezero igneous rocks defined the same isotope mixing lines as the shergottites (Fig. 2), then the hypothesis that Mars underwent global-scale differentiation at around 4.52 Ga through solidification of a Martian magma ocean would be supported. This would reflect the likelihood that the shergottites are not from the Jezero region so that their isotopic systematics would be typical of the majority of Martian basaltic magmatism, justifying their use to constrain global-scale differentiation processes. Igneous samples from such a locality would also serve to test the hypothesis that the complexity of magmatic evolution is related to the location of the samples on Mars. For example, lateral heterogeneity of the mantle would be implied if samples with a range of ages from a single location shared a common simple (two-stage) or complex (multistage) evolutionary history. On the other hand, if samples from the Jezero region demonstrate evidence for both simple and complex evolutionary histories, then both types of sources probably underlie the area. This would be more suggestive of a vertically stratified mantle that was sampled through magma extraction at various depths. Although these scenarios are oversimplified given the geologic complexity of natural systems, they underscore the critical role that the location of samples has in constraining their origins, their relationships to other samples, and the validity of using individual samples or sample suites to inform evolutionary processes on a global scale.

Defining the Nature of Melting Reactions in the Martian Mantle

The parent/daughter ratios (^{87}Rb/^{86}Sr, ^{147}Sm/^{144}Nd, and ^{176}Lu/^{177}Hf) of the source regions of the Martian meteorites can be calculated from their initial Sr, Nd, and Hf isotopic compositions, assuming primordial differentiation occurred at 4.52 Ga (e.g., refs. 12, 13, 21, and 25). For the shergottites, which have simple two-stage evolutionary histories, the calculated parent/daughter ratio is a direct estimate of the meteorite sources at the time of melting. In contrast, for the nakhlite/chassignites that have undergone multiple stages of evolution, the calculated parent/daughter ratios represent time-averaged values that are unlikely to be characteristic of their source at the time of melt production. These calculations lead to the unexpected observation that the ^{147}Sm/^{144}Nd of the shergottite whole rocks is significantly higher than the ^{147}Sm/^{144}Nd calculated for their sources (Fig. 3*A*). Thus, the shergottites exhibit evidence that elemental behavior during magma genesis was distinct from, and opposite to, that seen for the nakhlite/chassignites or on other inner Solar System bodies (13, 19, 25). In contrast, the ^{87}Rb/^{86}Sr and ^{176}Lu/^{177}Hf ratios of the shergottites are similar to, or more elevated than, the ratios inferred for their source regions, consistent with the expected partitioning behavior of these elements in most magmatic systems (Fig. 3*B*). Note that interpreting the behavior of Rb/Sr during melting is complicated by the fact that Sr can be added to meteorites found in desert environments and through the accumulation of plagioclase. Nevertheless, Rb seems to behave more incompatibly than Sr, and Lu clearly behaves more compatibly than Hf (24, 25), as is typical of melting processes inferred for the Earth and Moon. This demonstrates that the difference in ^{147}Sm/^{144}Nd calculated for the shergottites and their sources does not reflect fractionation by multiple melt extractions from a single mantle source as suggested by Borg et al. (13) because although this process would produce melts that had ^{147}Sm/^{144}Nd > ^{147}Sm/^{144}Nd of their sources, it would also yield melts with ^{87}Rb/^{86}Sr < ^{87}Rb/^{86}Sr and ^{176}Lu/^{177}Hf > ^{176}Lu/^{177}Hf of their sources, contrary to what is observed. Instead, ^{176}Lu/^{177}Hf (and probably ^{87}Rb/^{86}Sr) appear to be fractionated in the opposite direction, implying that the unexpectedly elevated ^{147}Sm/^{144}Nd of the shergottites is a result of a close-system melting or crystallization process occurring at or near the time of melt generation.

The ^{87}Rb/^{86}Sr, ^{147}Sm/^{144}Nd, and ^{176}Lu/^{177}Hf of the nakhlite source regions, although plotted in Fig. 3, cannot be calculated with confidence from their isotopic data because the sources did not evolve through well-defined stages of evolution as observed for the shergottites. Nevertheless, the initial ^{143}Nd/^{144}Nd and ^{176}Hf/^{177}Hf of the nakhlite/chassignites are elevated relative to chondritic meteorites (14, 67, 68), indicating derivation from sources that are incompatible-element depleted (e.g., have superchondritic ^{147}Sm/^{144}Nd and ^{176}Lu/^{177}Hf). In contrast, the ^{147}Sm/^{144}Nd and ^{176}Lu/^{177}Hf of the nakhlite whole rocks are subchondritic and are therefore lower than the corresponding ratios inferred for their sources, which is consistent with expected fractionation of Sm, Nd, Lu, and Hf during partial melting of typical mafic mantle minerals. This relationship is consistent with the time averaged parent/daughter ratios of the nakhlite sources plotted in Fig. 3. Thus, the behavior of Sm/Nd and probably all REE differs significantly during melt generation from the shergottite and nakhlite/chassignite source regions, whereas Lu/Hf and probably Rb/Sr behave similarly in both meteorite groups.

The unexpected relationship between the ^{147}Sm/^{144}Nd of the shergottites and their sources can be accomplished in two ways. One possibility is that a phase strongly enriched in HREE relative to LREE was consumed during partial melting of the mantle. For instance, majoritic garnet has been postulated to exist in the Martian mantle (45, 69, 70) and, if melted, has the appropriate REE systematics to increase the ^{147}Sm/^{144}Nd of the melts. Importantly, however, the ^{176}Lu/^{177}Hf ratios of the shergottites are lower than those of their source regions (25; Fig. 3*B*), inconsistent with consuming large amounts of garnet during melt production. Alternatively, a phase preferentially retaining LREE, such as plagioclase or phosphate, that remains in the mantle during partial melting could also explain the Sm-Nd systematics of the shergottites. This possibility, however, is contrary to our current understanding of melting reactions and partitioning of REE in terrestrial mantle lithologies. For example, LREE-enriched phases such as plagioclase and phosphate are not expected to be retained in the mantle during melting, and plagioclase retention would produce melts with strongly negative Eu anomalies that are not observed in the SNC suite of meteorites. Nevertheless, it is difficult to avoid calling upon an unidentified restite phase unless the assumption that the shergottite sources were produced in two stages of evolution is incorrect. This also seems unlikely, however, given the well-behaved isotopic mixing relationships of the shergottite sources, the linearity of the ^{146}Sm-^{142}Nd isochron, and the similarity between the isotopic systematics of the sources of Martian and lunar basaltic rocks (e.g., refs. 17, 18, 24–27, 29–35, 37, 38, and 71). Thus, although a residual phase enriched in LREE is not evident in lunar and terrestrial igneous systems, perhaps it could be stabilized under conditions unique to Mars.

Another difference between the nakhlites and shergottites involves the magnitude of their radiogenic ^{182}W excesses. The shergottites have ε^{182}W ranging from 0.37 to 1.48 (ε^{182}W is the deviation from terrestrial standards in parts per 10^4), where all but the most LREE-depleted shergottites have relatively similar ε^{182}W averaging around 0.4 (27). By contrast, the most LREE-depleted shergottites exhibit more variable and elevated ε^{182}W. A key observation is that the ε^{182}W of the shergottites correlates with ε^{142}Nd, indicating that Hf/W fractionation is associated with Sm/Nd fractionation during primordial silicate differentiation occurring during the first ~40 Ma of Solar System history (2, 27). In contrast, the nakhlites demonstrate considerably more elevated and more uniform ε^{182}W from about 2.8 to 3.0 (2). Although the nakhlite/chassignites do not require Sm to behave less compatibly than Nd during partial melting, the highly elevated ^{182}W of the nakhlites suggests that the source of the nakhlites either formed considerably earlier than the shergottite sources or alternatively, has a more elevated Hf/W ratio. Using the differentiation model developed by Kruijer et al. (27), and assuming a differentiation time of at 4.52 Ga, the ^{180}Hf/^{184}W

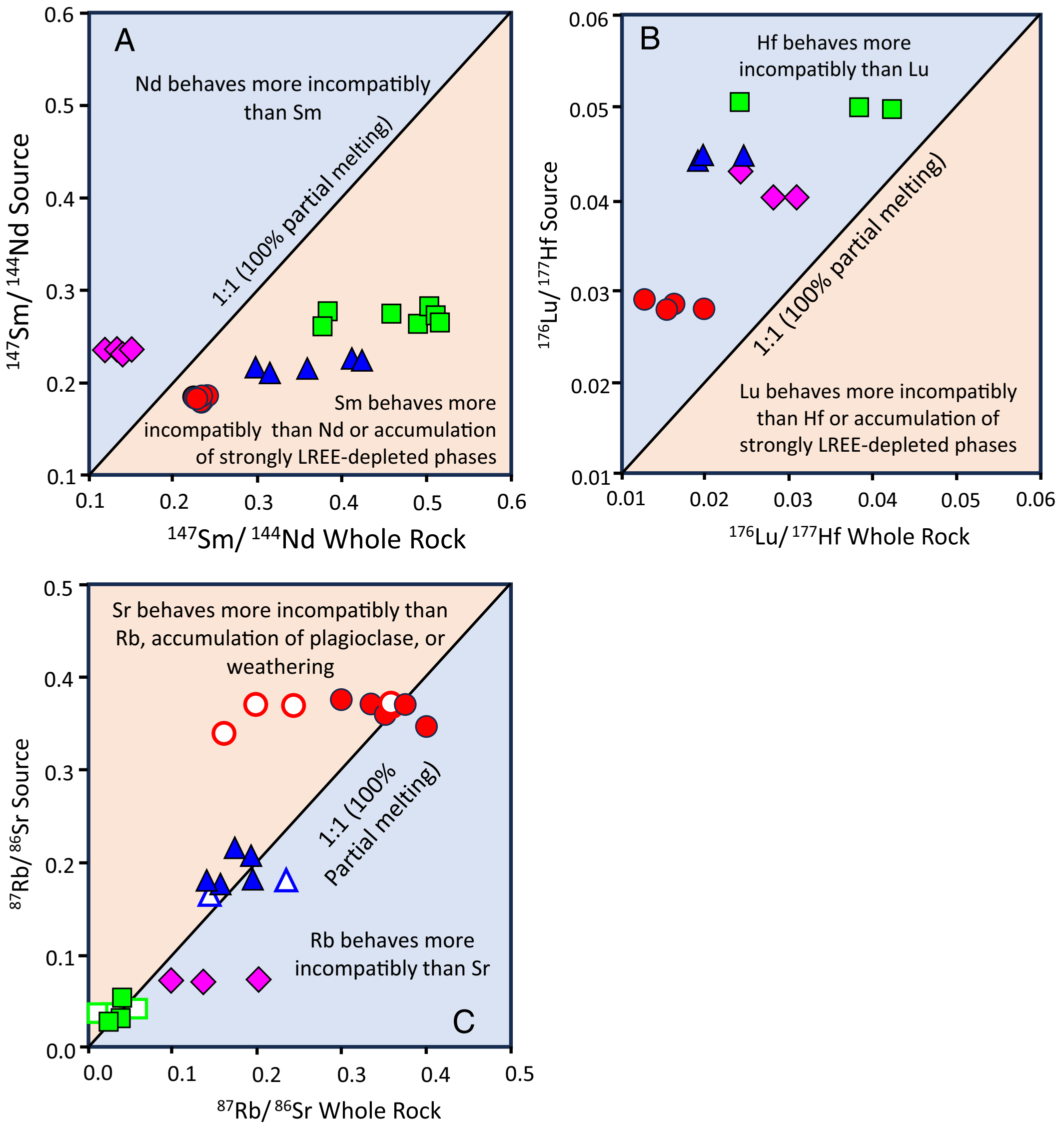

Fig. 3. Parent/daughter ratios calculated for shergottite sources are plotted against similar ratios measured in their whole rocks. (*A*) ^{147}Sm/^{144}Nd whole rock versus ^{147}Sm/^{144}Nd source, (*B*) ^{176}Lu/^{177}Hf whole rock versus ^{176}Lu/^{177}Hf source, (*C*) ^{87}Rb/^{86}Sr whole rock versus ^{87}Rb/^{86}Sr source.The blue fields represent the relationship between parent and daughter elements expected during partial melting in which Rb behaves more incompatibly than Sr, Nd more incompatibly that Sm, and Hf more incompatibly than Lu. Panel *A* demonstrates that Sm behaves more incompatibly than Nd on Mars. Data sources and symbols are the same as Figs. 1 and 2.

of the nakhlite/chassignite source region must be about 88 times the best estimate of the bulk planet defined by chondritic meteorites if it formed concurrently with the shergottite sources. In contrast, for this same differentiation age, the calculated ^{180}Hf/^{184}W of the shergottite sources range from 4 to 41, i.e., up to 22 times lower than for the nakhlite sources. The magnitude of the Hf/W fractionations required to explain the ^{182}W variations among shergottites and nakhlites is consistent with either an as yet unidentified phase in the LREE-depleted shergottite and nakhlite/chassignite sources in which Hf is strongly compatible or a high proportion of a phase, such as clinopyroxene, in which Hf is moderately incompatible (e.g., Kd Hf = 0.10 to 0.44; GeoRef database) but still more compatible than W. Finally, the notion that W partitioning is strongly affected by oxidation state (e.g., ref. 72) alongside the observation that Martian melts are variably oxidized (73) may imply that oxidation state played an important role in the fractionation of Hf from W during silicate crystallization.

Collectively, the isotopic systematics of the SNC meteorites suggest that there is a misunderstanding of the phases, mineral modes, partitioning behavior of trace elements, or evolution of the mantle through time. Because isotopic systems are based on trace elements, the presence of a few key minor unidentified phases that disproportionally affect radiogenic isotopic systematics may be all that is required to produce the observed behavior of Sm, Nd, Hf, and W. Nevertheless, the presence of these phases in the Martian mantle would underscore the fundamental differences in the conditions under which melts are produced on Mars compared to other terrestrial planetary bodies. The disparate behavior of Sm/Nd in the shergottites compared to the nakhlites/chassignites implies that the mechanisms of melt generation and source mineralogy are fundamentally variable on Mars in space or time. This likely requires the generation of the shergottites and nakhlite/chassignites in either different regions of a vertically or laterally heterogeneous mantle or at different times in an evolving mantle. Additional samples with different ages derived from different locations on Mars, such as the Jezero crater region, might help to better understand the mineralogy, composition, physical conditions of melt production, and temporal evolution throughout the Martian mantle. For example, such ~3.8 Ga samples (64) might preserve evidence for phases that are not present in the SNC meteorite suite, constrain the conditions in the mantle early in Martian history that are not represented in the current meteorite suite, or if primitive enough, define starting compositions for experiments that constrain the conditions of the early Martian mantle. Linking individual samples to specific regions may be a way to at least constrain the scale of mantle mineral heterogeneity. Finally, confirming the apparent link between the behavior of Sm/Nd and Hf/W during melting and the complexity of the processing of the Martian sample source regions (i.e., two-stage or multistage evolutionary histories) might elucidate whether elemental fractionation observed in the meteorite suite is associated with primary differentiation of Mars or secondary processes associated with later geologic activity. In any case, additional igneous samples are needed to ultimately define the compositional and mineralogical variability of the Martian mantle and how this variability is reflected in the composition of magmas sampled on the surface. Old igneous samples from locations that are distinct from where the SNC meteorites derive from are ideal for this endeavor.

Understanding the Evolution of Martian Magmas

Another outstanding question arising from the radiogenic isotopic systematics of the shergottites involves their petrogenesis and, specifically, the physical nature of the evolved component that appears to contribute to the geochemical and isotopic variability of the shergottites. The relationship between the $^{87}Rb/^{86}Sr$, $^{147}Sm/^{144}Nd$, and $^{176}Lu/^{177}Hf$ calculated for the shergottite sources is presented in Fig. 4. From these plots, it is apparent that the sources of the shergottites fall along mixing lines defined by a mantle-like endmember and an evolved endmember (13, 24, 25). It has been suggested that the evolved endmember represents an incompatible element–enriched late-stage crystallization product of the Martian magma ocean that is ostensibly similar to lunar urKREEP (5, 25, 39, 45) or, alternatively, the incompatible element–enriched evolved crustal component (74–77). Incompatible element–enriched lithologies from other planetary bodies provide some insights into the relevant types of materials. One material is lunar urKREEP, which has a basaltic lithology and is characterized by exceedingly elevated abundances of K, REE, and P (78) allowing the addition of a tiny amount to strongly modify its isotopic systematics of a primitive parent magma. Although less enriched in incompatible elements, several other appropriate lithologies exist that could modify the isotopic systematics of primitive melts. For instance, granitic lithologies from the Moon containing a combination of K-feldspar, quartz, and plagioclase are enriched SiO_2 and incompatible elements (79) and might be an appropriate analog for Martian felsic crust. Terrestrial analogs for an enriched Martian crustal component include igneous felsic crustal materials or even alkali-basalts. Finally, the Curiosity rover has identified alkali-enriched crustal materials on the Martian surface that have elevated SiO_2 and $Na_2O + K_2O$ abundances (80).

Defining the host lithology for the enriched component in the shergottites is important because it dictates whether Mars is more likely to have evolved similarly to the Moon or the Earth, underscoring the legitimacy of extrapolating models of planetary evolution between inner Solar System bodies. If the evolved component is a late-stage crystallization product of primordial differentiation of a Martian magma ocean, then a clear relationship to the differentiation mechanisms inferred for the Moon would be established. By contrast, if the evolved component is an ancient felsic material but produced by secondary (nonprimordial) processes, then processes more akin to those observed on Earth are probably the best analogs for Martian magmatism. In both cases, the age constraints based on primordial differentiation by radiogenic isotope systems remain mostly valid. However, if the evolved component is a relatively young material derived by secondary processes occurring substantially after primordial differentiation, then the current age constraints based on radiometric isotopic systematics (Fig. 2) would be invalid because the model isochrons would not represent mixing between complementary and contemporaneous primitive and evolved sources. In either scenario, the evolved endmember must be strongly enriched in Rb relative to Sr, Nd relative to Sm, and Hf relative to Lu, be produced when ^{146}Sm and ^{182}Hf were still alive, and have remained isolated until the time of shergottite magma production in order to preserve the well-defined radiogenic isotope systematics of the shergottites (e.g., refs. 1, 3, 4, 21, 27, and 71).

Discerning which of these two mechanisms is responsible for the incompatible trace element and isotopic systematics of the shergottites is not straightforward because there are several problems associated with both. First, whereas urKREEP is a ubiquitous component in many rocks found on the lunar surface, there is no evidence yet for an analogous late-stage incompatible trace element–enriched reservoir on the surface of Mars. Thus, the existence of such an enriched endmember on Mars is speculative and probably would not have been invoked in models for early mantle differentiation if it had not first been observed on the lunar surface. Furthermore, mixing typical lunar mafic cumulates and urKREEP-like components does not exactly reproduce all the isotopic mixing relationships of the shergottites (Fig. 4*C*; Model 1). Specifically, the elemental abundances of Sm, Nd, Lu, and Hf must be lowered relative to Rb and Sr abundances to reproduce the isotopic systematics of the shergottites (Fig. 4; Model 2). This could imply that late-stage Martian magma ocean cumulates are compositionally different from urKREEP, perhaps because a Martian magma ocean does not crystalize the same phases as a lunar magma ocean, or that the bulk composition of Mars differs from that of the Moon. An alternative possibility is that another enriched endmember, such as evolved felsic crust, was involved in the petrogenesis of the shergottites. Assimilating even modest amounts of felsic crust with basaltic magmas, however, presents a thermal quandary because basaltic magmas simply do not have enough heat (e.g., refs. 81–83) unless assimilation is accompanied by significant amounts of fractional crystallization (e.g., ref. 84). Although melting of wall rock using the latent heat of crystallization alleviates the thermal concerns, it is expected to produce evolved melts as a result of both the removal of mafic minerals and the addition of felsic assimilants. This process should, therefore, be manifest in the shergottite suite by corresponding increases in geochemical indices of differentiation, such as Mg#, and radiogenic isotopic composition of the parental magmas (21). The absence of such correlations implies that assimilation, at least as it is understood in terrestrial magma systems, has not occurred on Mars. One possibility is that the crustal

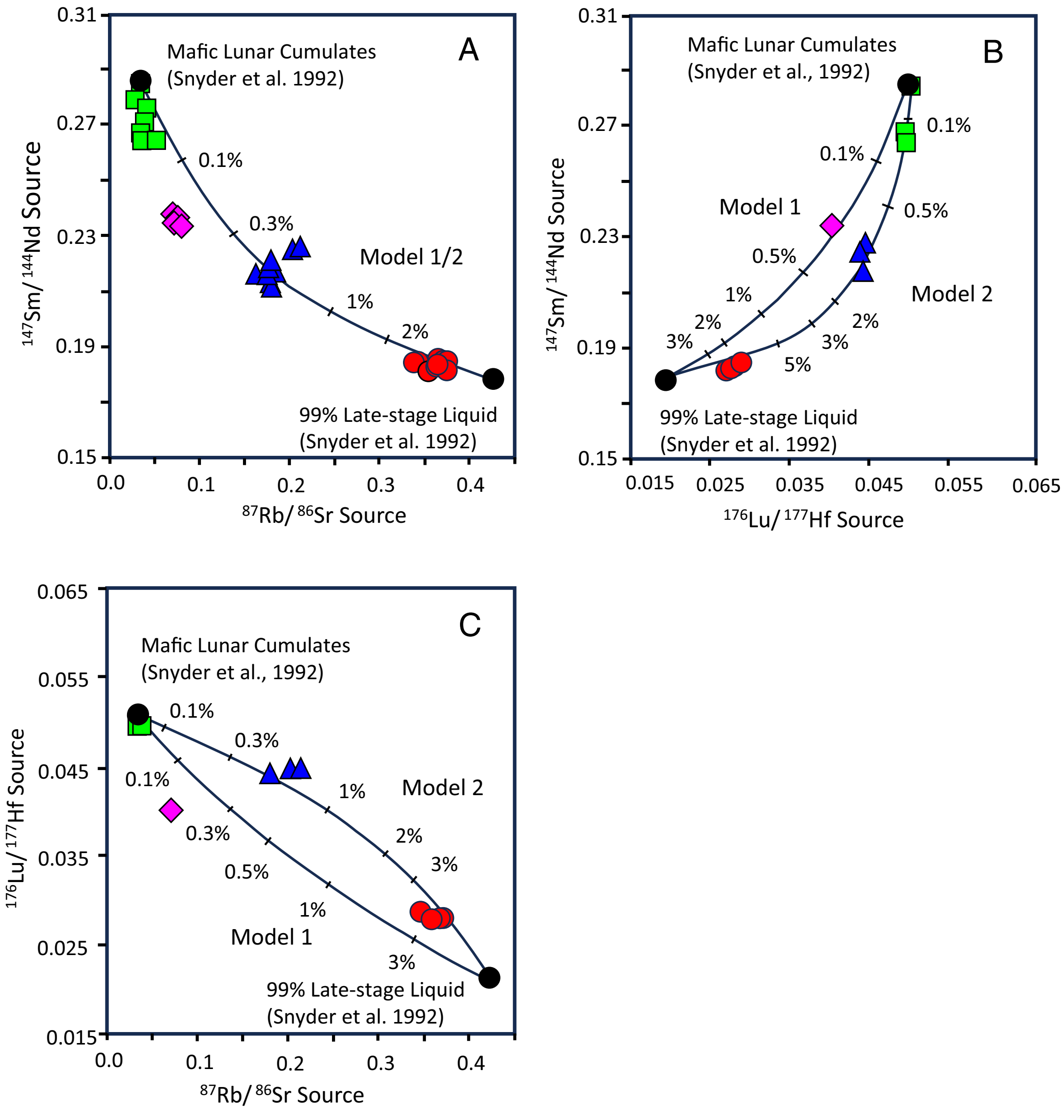

Fig. 4. Mixing relationships of shergottite sources. Isotopic ratios of sources calculated from shergottite isotopic systematics following (18). (*A*) $^{87}Rb/^{86}Sr$ source versus $^{147}Sm/^{144}Nd$ source, (*B*) $^{176}Lu/^{177}Hf$ source versus $^{147}Sm/^{144}Nd$ source, (*C*) $^{87}Rb/^{86}Sr$ versus $^{176}Lu/^{177}Hf$ source. Mixing diagrams consist of two models. In model 1, elemental abundances of mafic cumulates are estimated from models of ref. 10 and urKREEP from ref. 78. In model 2 the Sm-Nd and Lu-Hf abundances are 0.4 and 0.15, respectively times the urKREEP estimate of ref. 78. Note that ref. 74 demonstrated that estimates of Martian mantle and crust also satisfy mixing relationships in *A*. Data sources and symbols are the same as Figs. 1 and 2.

assimilant is so extremely enriched in incompatible elements that only a minimal addition would strongly leverage the isotopic systematics of the shergottites without affecting their major element compositions. This is essentially analogous to placing urKREEP in the Martian crust. The problem here is that, like Martian urKREEP, there is no evidence that this material exists on Mars.

Additional samples are required to determine the source of the evolved component on Mars, thereby elucidating the style of magmatic evolution. For example, a lunar style of magmatic evolution involving mixing of early and late-stage magma ocean crystallization products would be supported by the discovery of picrites or basalts with near primitive chemical and mineralogical features that had elevated incompatible element abundances and evolved Sr, Nd, and Hf isotopic systematics. Likewise, evolved felsic crustal samples, such as those initially observed at Gusev crater (85, 86), that exhibit evidence for derivation from strongly incompatible element–depleted sources by fractional crystallization would support this style of magmatic evolution by demonstrating that evolved magmas could be produced in a closed system without requiring assimilation of crust. In contrast, a series of related samples that demonstrated clear correlations between magmatic evolution (e.g., Mg#) and incompatible element enrichment of their sources (e.g., Rb/Sr) would support a more terrestrial style of geological evolution. Of course, identifying old, ca. 4.52 Ga felsic samples characterized by highly elevated incompatible element abundances and isotopic systematics that define the evolved end on the Sm-Nd and Rb-Sr mixing arrays (Fig. 4) would also support this model. Such evolved crust is argued to be present in the southern hemisphere (87), has been identified in Gale crater (86), and may be represented by small fragments in the NWA 7034 family of meteorites (88–92). Determining the Rb-Sr, Sm-Nd, and Lu-Hf isotopic systematics of new samples with these general characteristics that represent the oldest crust or primitive basaltic samples with isotopic systematics that differ from those currently in hand would help greatly to address this issue.

Understanding the Evolution of Mars

From the examples discussed above, it is evident that although a general understanding of the primordial evolution of Mars has been developed from the isotopic systematics of the SNC meteorites, a coherent model that accounts for all of the observations has yet to be put forward. We do not know how far the isotopic data measured in the meteorites can be extrapolated to constrain the nature and timing of global-scale differentiation processes. Nor do we understand the physical location of the various mantle and crustal reservoirs that are the sources of the Martian meteorite suite. In fact, processes as simple as partial melting and magma genesis remain at least partially ambiguous. The fact that disparate evolutionary histories are derived from the two main groups of meteorites that comprise ~95% of samples currently in hand emphasizes our poor grasp of the igneous history of this planet. This should not be a surprise given the diversity of rock types identified from rover observations compared to the samples currently present in the meteorite collections. Rover observations have identified an array of igneous samples that do not seem to share much affinity with the meteorites, illustrating this fundamental bias. Most meteorites have relatively low SiO_2 and alkali-element ($Na_2O + K_2O$) contents, whereas rocks analyzed on the surface of Mars are characterized by similar or much higher SiO_2 and much higher alkali-element contents (e.g., refs. 80 and 93). The geochemistry of rocks analyzed on the surface of Mars most closely match the small (<5 mm) clasts in the NWA 7034 family of meteorites, most of which are significantly smaller than 200 milligrams and consequently too small to determine the isotopic systematics of their sources. It is apparent that even a complete understanding of the origin and evolution of the meteorite samples that are currently in hand is not sufficient for understanding how Mars formed and evolved.

To understand the igneous evolution of Mars, samples from known locations are needed. These samples serve to link specific events and sample/source characteristics to physical locations on Mars allowing macroscopic observations to be used to further constrain physical processes. Samples from known locations also facilitate extrapolation of detailed sample measurements to a much broader scale through remote sensing observations. An example of such an extrapolation is calibrating the cratering curve used to estimate the age of surfaces on Mars. Meteorite studies are not useful in this regard because they derive from unknown surfaces. Instead, Martian curves are historically based on the lunar curve and estimated differences in cratering rate between the Moon and Mars (e.g., refs. 94 and 95). Samples from known locations, such as Jezero crater, would provide the only measured point on the Martian curve and would significantly refine the existing surface ages based on crater size-frequency distributions. To address questions of global-scale planetary evolution ultimately requires the acquisition of an expanded set of igneous samples. Sample suites from individual sites will constrain processes of magmatic evolution within local igneous systems. Comparison of these samples to the meteorite samples will provide a broad understanding of the origin and evolution of Mars. Igneous samples from the vicinity of Jezero crater and returned to Earth by the Mars Sample Return mission would be a strong step in this direction.

Data, Materials, and Software Availability. Previously published data were used for this work [Borg et al. (13, 18, 24), Kruijer et al. (27), Caro et al. (4), Foley et al. (2), Debaille et al. (3, 14, 25), Symes et al. (21)].

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